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Freshwater for resilience: a shift in thinking

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Humanity shapes freshwater flows and biosphere dynamics from a local to a global scale. Successful management of target resources in the short term tends to alienate the social and economic development process from its ultimate dependence on the life-supporting environment. Freshwater becomes transformed into a resource for optimal management in development, neglecting the multiple functions of freshwater in dynamic landscapes and its fundamental role as the bloodstream of the biosphere. The current tension of these differences in worldview is exemplified through the recent development of modern aquaculture contrasted with examples of catchment-based stewardship of freshwater flows in dynamic landscapes. In particular, the social and institutional dimension of catchment management is highlighted and features of social–ecological systems for resilience building are presented. It is concluded that this broader view of freshwater provides the foundation for hydrosolidarity.

Keywords: resilience; freshwater; aquaculture; adaptive management; co-management; ecosystem services

1. INTRODUCTION

Throughout history humanity has shaped nature and nature has shaped the development of human society (Turner *et al.* 1990; Redman 1999). Therefore, there are neither natural or pristine systems, nor are there social systems without nature. Instead, humanity and nature have been coevolving within the biosphere and its freshwater cycles in a dynamic fashion and will continue to do so (Norgaard 1994; Berkes & Folke 1998).

Land-use and land-cover changes by humans significantly affect key aspects of Earth system functioning (Falkowski *et al.* 2000). A large fraction of the world's available freshwater, nitrogen budget, carbon dioxide balance, fisheries production, and biotic turnover are driven by human activities (Vitousek *et al.* 1997). The same is true of the global phosphorus budget in relation to freshwater and coastal eutrophication (Bennett *et al.* 2001). The sheer magnitude of the production and application of polluting substances in rivers, groundwater and coastal areas has reached global dimensions (Foster & Chilton 2003; Meybeck 2003). Human activities dramatically accelerate evolutionary change in other species apparent in microbial antibiotic resistance to drugs, plant and insect resistance to pesticides, life-history changes in commercial fish stocks, rapid changes in invasive species, pest adaptation to biological engineering products, and emergence of diseases (Lindgren & Gustafson 2001; Palumbi 2001; Watson & McMichael 2001).

During the twentieth century the human population increased by a factor of four, the urban population by a factor of 13, water use by a factor of nine, sulphur dioxide emissions by a factor of 13, carbon dioxide emissions by a factor of 17, marine fish catch by a factor of 35 and industrial output 40 times (McNeill 2000). Crutzen & Stoermer (2000) coined the concept of the Anthropocene and Meybeck (2003) suggests that it took off after World War II. The Anthropocene is an era where most aspects of the structure and functioning of Earth's ecosystems cannot be understood without accounting for the strong influence of humanity (Folke *et al.* 2002). Social–ecological coevolution now takes place also at the planetary level and at a much more rapid and unpredictable pace than previously in human history.

Despite tremendous improvements in technological, economic and material well-being, in some parts of the world, development of human society in all parts of the world relies on the capacity of the biosphere to support and sustain social and economic development. Freshwater is the bloodstream of the biosphere's capacity (Ripl 2003), the breath of the Earth (Long *et al.* 2003). In a situation where humanity shapes freshwater and ecosystem dynamics at all scales, and across scales, this support capacity should no longer be taken for granted. The luxury of living with a self-repairing and forgiving biosphere seems to be history. The challenge in this new situation is to actively enhance and strengthen the capacity of the biosphere to support and sustain social and economic development and to explicitly recognize the role of freshwater in this context (Rockström *et al.* 1999).

It requires a shift in thinking from focusing on controlling change in an engineering fashion for optimal solutions to accept that change is the rule rather than the exception (Holling & Meffe 1996; van der Leeuw 2000). The old way of thinking implicitly assumes a stable and infinitely resilient environment. The new perspective recognizes that resilience can and has been eroded and that the challenge facing humanity is to try to sustain

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desirable pathways for development in the face of change (Carpenter *et al.* 2001; Folke *et al.* 2002). The concept of resilience shifts perspective from the aspiration to control change in systems assumed to be stable, to sustain and enhance the capacity of social–ecological systems to cope with, adapt to, and shape change and learn to live with uncertainty and surprise (Gunderson & Holling 2002; Berkes *et al.* 2003).

This article is about this shift in thinking and its implication for the human relationship to freshwater and its sustainable use. The first section presents the resilience perspective for social–ecological sustainability. This view is contrasted in the next section by the recent development of modern aquaculture in lakes and coastal areas, a monoculture approach that seeks to increase seafood production in an optimal and controlled fashion. In many respects modern aquaculture resembles those modern agricultural production systems that focus on controlling yield of a target resource by removing diversity and disturbance in environments assumed to be fairly stable and predictable. There is little appreciation for the existence of a living dynamic ecosystem of which the farming is a part and on which it ultimately depends. Freshwater is seen as an input for production or as a medium in which the farming takes place. Such simplified production systems diverge from a catchment-oriented approach for management of freshwater and ecosystem services, and their inter-linkages (Falkenmark 2000), in dynamic, complex and coupled social–ecological systems (Berkes & Folke 1998; Walker *et al.* 2002). Adaptive co-management systems (Olsson *et al.* 2004) may be well suited for catchment management.

These two sections highlight fundamental differences in perception among actors concerning human activities and our relationship with the biosphere. They illustrate that the underlying worldview or pre-analytic vision (Daly & Cobb 1989) strongly influences the direction of policy and management of the life-supporting environment. Unfortunately, the underlying worldview is seldom put on the table when actions for the future are discussed, but it will strongly influence the direction and potential for a sustainable future. In this context, the significance of the social dimension for successful freshwater management is exemplified through the development of adaptive co-management systems based on Swedish experiences. Their potential and significance in catchment management is also addressed. It is concluded that the management perception has to expand from viewing freshwater simply as a resource to an explicit recognition of the diversity of freshwater functions in catchments, including the essential role of freshwater in social–ecological resilience. This requires generating knowledge and understanding of the dynamic interplay between hydrological, ecological and social issues in ongoing learning processes, and not only in aquatic but also terrestrial ecosystems (Rockström *et al.* 1999). It also requires an active management of freshwater for ecosystem capacity and resilience in societal development.

2. THE CONCEPT OF RESILIENCE

Ecosystems are complex, adaptive systems that are characterized by historical dependency, nonlinear dynamics, threshold effects, multiple basins of attraction and limited predictability (Levin 1999). Assessing and evaluating sustainability in the context of complex systems (Kauffman 1993; Holland 1995) is considered a frontier of interdisciplinary research (Ludwig *et al.* 2001). Complex systems thinking is, for example, used to bridge social and biophysical sciences to understand climate, history and human action (McIntosh *et al.* 2000), assessments of regions at risk (Kasperson *et al.* 1995), syndromes of global change (Petschel-Held *et al.* 1999) and how to link social and ecological systems for sustainability (Costanza *et al.* 1993).

Resilience has been proposed as an essential factor underlying the sustained production of ecosystem services (table 1) in social–ecological systems faced with uncertainty and surprise (Gunderson & Holling 2002). Vulnerability is the antonym of resilience (Kasperson & Kasperson 2001). Resilience is defined as the amount of disturbance a system can absorb and still remain within the same state or domain of attraction (Holling 1973, 1996). Resilience also encompasses the ability for reorganization and renewal subject to disturbance and change. The definition includes the degree to which the social–ecological system is capable of self-organization (versus lack of organization, or organization forced by external factors) and the degree to which the system expresses capacity for learning and adaptation (Carpenter *et al.* 2001; Berkes *et al.* 2003). The role of freshwater dynamics and management in relation to resilience is an unexplored area.

Resilience can be affected by human alteration of freshwaterlows and management that simplifies terrestrial and aquatic environments. Ecological research has shown that ecosystems with reduced resilience may still maintain function and generate services, i.e. may seem to be in good shape. But when systems faced with diminished resilience are subject to a sudden event (like a flood or heavy rainfall), a critical threshold may be reached and they may slide into another less desirable state with a reduced capacity to supply life-supporting functions for societal development (Scheffer *et al.* 2001). In a resilient social–ecological system disturbance events have the potential to create opportunity for reorganization, development and also innovation. In a vulnerable social–ecological system even a small event may be devastating for the persistence of the system. This is illustrated in figure 1.

There are many examples where human behaviour unconsciously contributes to a modification of the important variables that structure and sustain desirable states, through, for example, land-use change, redirection of freshwater flows and change in freshwater quality (Carpenter *et al.* 2001; Gunderson & Pritchard 2002), and may thereby cause loss of resilience (van der Leeuw 2000). In such situations, society becomes more susceptible to surprise and crisis but people are often ignorant about it. Decision-making agents and actors involved in management create vulnerability without knowing it.

3. THE PATHOLOGY OF NATURAL RESOURCE MANAGEMENT

Having a strong sector-based focus, conventional resource management often aims at producing a few target resources like timber and crops in monocultures, single

Table 1. Examples of freshwater functions for ecosystem services.
(Ecosystem development is preconditioned by freshwater, the biota self-organizes around freshwater flows and ecosystem services are generated.)

freshwater functions	example of ecosystem services
soil moisture for biomass production, transpiration, decomposing and recycling of organic material and nutrients in terrestrial ecosystems	crop and timber production carbon sequestering waste assimilation soil surface protection
rainfall, plant, micro- and soil organism interactions in terrestrial ecosystems	facilitates infiltration through soil permeability and interception flood control
oxic and anoxic environments in wetlands	nutrient retention habitats that sustain bird biodiversity recreational values
groundwater and run-off recharge into lakes and rivers	spawning grounds for fish seed dispersal
moisture feedback in tropical forests	genetic diversity
occasional water holes in dryland areas, and water generated structural patterns that trap seeds and initiate plant growth	wildlife diversity cattle production tourism values pollination
interactions between dry/wet periods	pest control of insects

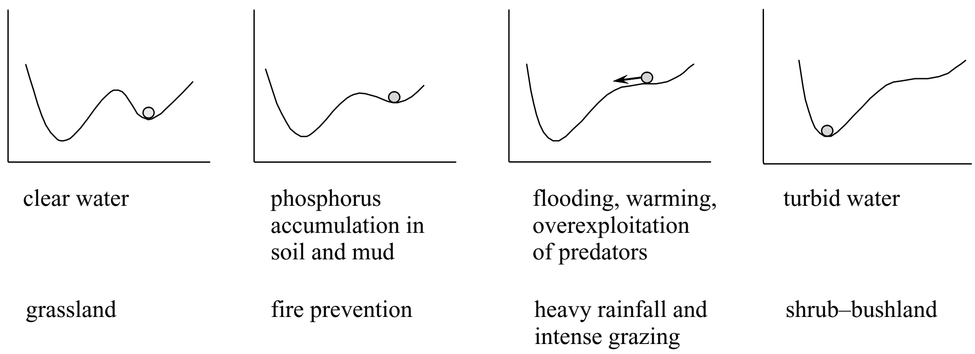

Figure 1. Shifts between states in lakes and rangelands caused by human-induced loss of resilience (modified from Deutsch *et al.* 2003). Water clarity in lakes does not seem affected by inflow of nutrients from the surrounding catchment until a critical threshold when the lake shifts abruptly from clear to turbid, eutrophied waters. In rangelands the shift is driven by fire and grazing pressure under highly variable rainfall conditions. Persistent high grazing pressure for livestock production can shift the grass-dominated state to the less productive (from a human use perspective) state of dominance by small trees and shrubs. Freshwater is a key agent in both examples.

fish species, or certain livestock. Freshwater is in many instances also treated as a target resource, disregarding its essential role as the bloodstream of the biosphere. Target resources are primarily managed for economic output by rules and regulations made by technical experts often of centralized management and disconnected from learning and recognition of hydrological and ecological dynamics (Gunderson *et al.* 1995). The emphasis of such management is on securing steady flows of predictable yield levels. Controlling environmental variability and natural disturbance becomes essential in such systems, because fluctuations impose problems to meet predicted production goals (Holling & Meffe 1996). Thus, managers seek to command and control these processes in an attempt to stabilize resource outputs (Carpenter & Gunderson 2001).

(a) *Modern aquaculture*

A recent example is the fast-growing aquaculture industry that specializes in production of high-valued species, like salmon and shrimp, in monocultures. Salmon are farmed in net pens in dense populations in lakes and coastal areas of temperate regions from Norway to Chile (Folke & Kautsky 1989). Shrimp are produced in ponds, mainly in coastal areas of tropical nations. Shrimp need brackish water, and large areas of mangrove forests have been removed to make way for shrimp production. In Thailand, shrimp farms have been located further upstream, adding salt to the freshwater diverted to the ponds (Lebel *et al.* 2002).

Seafood production by modern aquaculture is often put forward as the solution to overfishing of continental shelves. It is often argued that aquaculture relieves pressure on deteriorating wild fish stocks and that this new technology helps remove environmental constraints on human society. The growth of salmon and shrimp production has been substantial. Between 1986 and 1996 the yield from salmon farms went from 60 000 tons to 650 000 tons yr^{-1}. The corresponding annual production for shrimps was 100 000 tons in the early 1980s and 700 000 tons in the mid-1990s. Aquaculture as a whole contributes to more than 25% of global seafood production and is growing at a rate of 6–7% per year (Naylor *et al.* 2000).

However, such 'throughput systems' (Daly & Cobb 1989) depend heavily on external inputs, generate large amounts of waste and release chemicals used in production (Folke & Kautsky 1992; Folke *et al.* 1997). Salmon farming needs fishmeal to feed the salmon, which requires substantial support from ecosystems to sustain production. It has been estimated that farms in the Nordic countries demand a support of marine food webs for feed production over an area *ca.* 40 000–50 000 times the surface area of the pens in which the salmon is farmed (Folke *et al.* 1998). On a global basis, farming of species like salmon and shrimp uses *ca.* 2–3 kg of fishes from the sea for each kilogram of seafood production. Furthermore, habitat conversion for shrimp farming in coastal areas reduces wild fish biomass by an estimated 0.5 kg per kilogram of farmed shrimp (Naylor *et al.* 2000).

The increasing scale of these enterprises is now causing substantial environmental consequences. Conversion of coastal ecosystems to aquaculture ponds deteriorates mangrove ecosystems and nursery areas that support ocean fisheries. Lakes and coastal waters are euthrophied by fish farms through discharge of nutrients. Fish farming also impacts aquatic ecosystems through the introduction of exotic species, spread of diseases and use of chemicals and medicals. Rapid growth in shrimp and salmon farming has caused environmental degradation, while contributing little to world food security (Naylor *et al.* 1998).

Resource management systems like the ones described above are often successful in increasing yield in the short term. Success seems to generate a belief system of human progress as increasingly independent of nature. Nature can be conquered, controlled and ruled. The life-supporting environment is transformed into an economic sector for production of social value (Gunderson *et al.* 1995). It becomes a matter of human preferences (Pritchard *et al.* 2000). Short-term success seems to make people mentally disconnected from and illiterate about their ultimate dependence on the life-supporting environment, and incentives for responding to environmental feedback disappear.

(b) *The command-and-control fallacy*

This pattern of environmental management, briefly summarized and simplified above, has been termed the 'pathology of natural resource management' (Holling & Meffe 1996) and has been described for several sectors, in several regions of the world and over different temporal scales (e.g. Regier & Baskerville 1986; Gunderson *et al.* 1995; Redman 1999; Carpenter & Gunderson 2001). According to Holling (2003) the regional pathology has the following features.

(i) The policies and development initially succeed in removing disturbance and enhancing growth.
(ii) Implementing agencies initially are responsive to the ecological, economic and social forces, but evolve to become narrow, rigid and myopic. They become captured by economic dependents and the perceived needs for their own survival.
(iii) Economic sectors affected by the resources grow and become increasingly dependent on perverse subsidies.
(iv) The relevant ecosystems gradually lose resilience to become fragile and vulnerable and more homogeneous as diversity and spatial variability is reduced.
(v) Crises and vulnerabilities begin to become more likely and evident and the public begins to loose trust in governance.

In rich regions the resulting crises have led to sudden learning with expensive actions directed to reverse the worst of the consequences of past mistakes. In poor regions the result has often been dislocation of people, increasing uncertainty, impoverishment and a poverty trap (Gunderson & Holling 2002).

Human activities that simplify ecosystems for production of valuable target resources only tend to erode resilience and make social and economic development vulnerable to change (van der Leeuw 2000; Folke *et al.* 2002). This is obvious in fisheries (Pauly *et al.* 2002). Ludwig *et al.* (1993) claim that the command-and-control pathology has directed fisheries into a large-scale fishing concentrated on few species; has led to an over-capacity of the fishing fleet; and to degradation, and to a great extent the depletion, of an important food source; and does not respond to signals from the ecosystem, i.e. lacks functioning feedback mechanisms.

Historical overfishing has eroded the capacity of coastal areas to maintain viable fish populations at higher trophic levels and assimilate waste (Jackson *et al.* 2001). This capacity is now further challenged by modern aquaculture's continued growth and impact on coastal environments. There is an obvious risk that the recent development of fish farming in monocultures will exacerbate the command-and-control fallacy described above. Already, the short-term success of the newly developed industry seems to remove incentives to respond to environmental feedback (unless legally or economically enforced) and support a worldview among its proponents of human progress as independent and disconnected from the biosphere.

Freshwater managers should critically evaluate to what extent their approaches to confronting freshwater issues are based upon a narrow engineering view and a fragmented perspective that contributes to the removal of incentives for responding to environmental feedback. Is freshwater viewed as a commodity—a target resource—taken out of its biogeophysical context, or is it viewed as the bloodstream of the biosphere and managed for enhancing social–ecological resilience? The pervasive pollution of freshwater resources (Meybeck 2003) and the substantial redirection of freshwater flows causing serious salinization on the Australian continent (Gordon *et al.* 2003) may reflect the existence of a pathology or at least a lack of a systems perspective to freshwater issues.

4. CATCHMENT MANAGEMENT AND SOCIAL–ECOLOGICAL RESILIENCE

In recent years catchment-based freshwater management has gained momentum (Falkenmark 2000; Wallace *et al.* 2003), reflected for example in the Working for Water Programme of South Africa, the attempts towards catchment management in Australia or the move towards a landscape division into catchments within the European

Union. Recently the Global Water Partnership has broadened its approach to include and account for the significance of freshwater in the structuring and dynamics of all life-support systems of the Earth (Falkenmark 2003).

Integrated water resources management is in a process of expanding the focus from human uses of freshwater as a resource to the role of freshwater in integrated eco-hydrological catchment management (Falkenmark & Folke 2002). The expansion in perception from freshwater as a resource to freshwater as the bloodstream of the biosphere implies an expansion of the system boundary from run-off to rainfall (Falkenmark 2000; Gordon *et al.* 2003). It implies recognition of the significance of water vapour—the breath of the Earth—in human well-being and societal development (Rockström *et al.* 1999; Rockström 2003). Freshwater and ecosystems interact in ways that contribute to the generation of ecosystem services for human well-being. The movement and dynamics of freshwater in the landscape, water availability in soils for plants production, moisture recycling in forest, recharge of ground water, rivers and lakes are fundamental for ecosystem resilience (table 1).

Catchment management is not a recent invention of contemporary society. Sophisticated irrigation systems have existed throughout the world (e.g. Ostrom 1990; Lansing 1991). The basic idea of catchment management goes back at least to the ancient Greeks. A sixteenth century Chinese print about tree restoration for river conservation implies that the Chinese knew about the relationship of forests, erosion and water quality. Written records going back to the sixteenth century illustrate that Swiss communities controlled catchments and used freshwater resources in an integrated fashion (Netting 1981). Berkes *et al.* (1998) provide a review of freshwater and ecosystem management in ancient systems.

(a) *The social dimension of freshwater management*

In contrast to the command-and-control approach, successful approaches strive to develop stewardships that interpret and respond to environmental feedback; that learn, build and store knowledge and understanding of freshwater and ecosystem dynamics; and that support flexible organizations and institutions and adaptive management processes in a manner that enhances resilience of social–ecological systems (Folke *et al.* 2003). This statement may seem like wishful thinking and a naive view impossible to implement in a world where social and economic drivers tend to overwhelm local efforts. In the following, two examples of the emergence of ecosystem management in Sweden will be presented. They reflect what we refer to as 'adaptive co-management systems' (Folke *et al.* 2002).

Adaptive co-management systems are flexible, often community-based systems tailored to specific places and situations, supported by and working with, various organizations at different levels. Adaptive co-management is a process by which institutional arrangements and hydrological and ecological knowledge are tested and revised in a dynamic, ongoing, self-organized process of learning-by-doing. The sharing of management power and responsibility may involve multiple institutional linkages among user-groups or communities, government agencies, and non-governmental organizations. Adaptive co-management relies on the collaboration of a diverse set of stakeholders operating at different levels, often in networks, from local users, to municipalities, to regional and national organizations, and also international bodies (Olsson *et al.* 2004).

In the two studies from Sweden the focus is on managing the different functions of freshwater in sustaining the capacity of landscapes to generate essential ecosystem services (Jansson *et al.* 1999; table 1). In the Lake Racken catchment of western Sweden, the task was to counteract the effects of acidification and secure the capacity of the lake and its catchment to produce fish and crayfish (Olsson & Folke 2001). In the Helgeå River catchment in southern Sweden, the challenge was to sustain a wetland landscape and its cultural and natural values in the lower parts of the catchment (Olsson *et al.* 2003).

In both cases, ecosystem management emerged through local initiatives as a response to environmental changes and events that were perceived as crises and acted upon. In the Lake Racken catchment these were acidification, a fish disease and overexploitation of aquatic resources. The social responses were

(i) generation of local ecosystem and hydrological knowledge, monitoring and management practices from the species to the catchment level;
(ii) local self-organization from a liming group to counteract acidification to the development of a fisheries association to sustain fisheries; and
(iii) shared management, exchange of experience between several fisheries associations and collaboration with municipality, county and other organizational and institutional levels (Olsson & Folke 2001).

The management system has developed during the past two decades and continues to develop towards an adaptive co-management system.

In the wetland landscape of the lower Helgeå River catchment the overall perceived threats were erosion of both natural and cultural values of the landscape that escalated over time. As a response to ineffective and uncoordinated management efforts by a range of actors to come to terms with these problems, a key individual created and transformed the management of the wetland landscapes into a stewardship of the lower part of the Helgeå River catchment that within a decade self-organized into an adaptive co-management approach. This change was made possible by a window-of-opportunity that resulted in the formation of a 'middle-men' association within the Municipality of Kristianstad's organization, Ecomuseum Kristianstads Vattenrike. This umbrella association for ecosystem management has demonstrated an ability to respond to environmental feedback and to develop new knowledge and understanding about ecosystem management needs. The scope of management in the area has widened to address a broader set of issues related to ecohydrological processes and management across scales. Management is based on collaborative processes including international organizations, national, regional and local authorities, non-profit associations and landowners.

Table 2. A sequence of self-organization towards adaptive co-management of catchments (Olsson *et al.* 2004).

scope of management widens from a particular issue to a broad set of issues related to hydrological and ecological processes across scales
management expands from individual actors, to groups of actors to multiple-actor processes
organizational and institutional structures evolve as a response to deal with the broader set of ecosystem issues
knowledge of ecosystem dynamics develops as a collaborative effort and becomes part of the organizational and institutional structures
social networks develop to connect institutions and organizations and facilitate information flows, identify knowledge gaps, and create nodes of expertise of significance for ecosystem management
knowledge for ecosystem management is mobilized through the social network and complements and refines local practice
in the time-series of events the ability to deal with uncertainty and surprise seems to be improved which increases the capacity to deal with future events

The steward played a key role in these processes by developing shared goals and a vision for catchment management, building trust, compiling and generating hydrological and ecosystem knowledge, defining an area for management, mobilizing broad support for change, and initiating collaborative learning involving stakeholders at different levels in society. The initiative of the key steward prevented the lower catchment landscapes from entering undesirable trajectories that would have resulted in a loss of ecosystem goods and services and welfare (Olsson *et al.* 2003).

The shift towards ecohydrological catchment management in Lake Racken is still vulnerable to change, and the management system is challenged by other worldviews and visions and may shift into another management system owing to lack of sufficient social–ecological resilience. The social–ecological management system in the lower parts of Helgeå river catchment seems to have passed its most vulnerable stages through a deepening and widening of the desirable social–ecological state. It seems like social–ecological resilience has been created by active management (Olsson *et al.* 2003).

These examples and other studies suggest a sequence in the development of self-organization of adaptive co-management systems of catchments. This sequence is presented in table 2.

Based on experiences from resource management Carpenter & Gunderson (2001) stress the need for continuously testing, learning and developing knowledge and understanding for coping with change and uncertainty in complex adaptive systems. It is largely recognized that catchment management will not be initiated or successfully implemented based on biogeophysical knowledge and understanding alone. The social dimension of catchment management has to be understood and accounted for to clarify features that contribute to the resilience of social–ecological systems (Barrett *et al.* 2001). Furthermore, flexible social networks and organizations that proceed through learning-by-doing seem better adapted for long-term survival than rigid social systems with set prescriptions for resource use (Gunderson & Holling 2002).

(b) *Social features for resilience*

We have started to dissect critical social features required for social–ecological resilience and flexible ecohydrological management of complex systems facing change and uncertainty. So far we have found that the following features are of significance in adaptive co-management:

(i) vision, leadership and trust;
(ii) enabling legislation that creates social space for ecosystem management;
(iii) funds for responding to environmental change and for remedial action;
(iv) capacity for monitoring and responding to environmental feedback;
(v) information and knowledge flow through social networks;
(vi) the combination of various sources of information and knowledge; and
(vii) sense-making and arenas of collaborative learning for ecosystem management.

There is no space here to elaborate on these in depth (see Olsson *et al.* 2004). But the key roles of leaders and stewards in social–ecological systems have to be stressed. Leaders and stewards provide vision, sense making, and build trust in the adaptive co-management process; facilitate horizontal and vertical linkages in catchment management; and serve as key players in institution building, organizational change and social networks (Pinkerton 1998; Westley 2002).

Through such functions leaders and stewards play an essential role in the development of a social memory for flexible ecohydrological management that evolves as a part of the adaptive co-management process. McIntosh (2000) defines social memory as the arena in which captured experience with change and successful adaptations, embedded in a deeper level of values is actualized through community debate and decision-making processes into appropriate strategies for dealing with ongoing change. Holling & Chambers (1973) and Folke *et al.* (2003) have identified several 'functional roles' in addition to leaders and stewards among actors that are significant parts of the social memory for catchment management. Ostrom (1990) has presented widely cited design principles for common property institutions involved in resource management and Holling & Sanderson (1996) have discussed a sequence of different human groups and their dominance during different stages of development of social–ecological systems.

(c) *Multi-level governance of catchments*

Low *et al.* (2003) propose that diversity in functions and response among actors in adaptive co-management systems, from the individual level to organizational and institutional levels seems to enhance performance as long as there are overlapping units of government that can resolve

Table 3. Shift in thinking and perspective on freshwater management.

from command-and-control	to complex systems
assume stability, control change	accept change, manage for resilience
predictability, optimal control	uncertainty, risk spreading, insurance
managing resources for increased yield, freshwater as input	managing diversity for coping with change, freshwater as bloodstream
technological change solve resource issues	adaptive co-management builds resilience
society and nature separated	social–ecological coevolution

conflicts, aggregate knowledge across scale, and ensure that when problems occur in smaller units, a larger unit can temporarily step in. From a social–ecological resilience perspective it seems to be beneficial if the capacity to deal with complex freshwater issues all the way up to the catchment level is widely dispersed across a set of actors located in multiple centres at different levels or polycentric governance (Imperial 1999; McGinnis 2000). Such flexible institutional arrangements, often non-hierarchical in structure, have been judged as inefficient and as a hindrance to optimal management. However, a growing literature on polycentric institutions is demonstrating that dynamic efficiency is frequently thwarted by centralized 'efficient' institutions and instead enhanced by systems of governance that exist at multiple levels with some degree of autonomy complemented by modest overlaps in authority and capability (Ostrom *et al.* 2002). In this way creativity of the self-organizing process is framed by a shared vision and by social memory (Folke *et al.* 2003).

Multi-level governance of complex ecosystems needs constant adjustment, which requires innovation, experimentation and learning (Lee 1993; Shannon & Antypas 1997; Ludwig *et al.* 2001). A diversified decision-making structure allows for testing of rules at different scales in loose networks and contributes to the creation of institutional dynamics important in adaptive co-management.

There seems to be great potential in addressing and combining the role of individual actors and agents of change with the formation of organizations and institutions for flexible catchment management. The cross-scale social arrangements in adaptive co-management systems seem particularly appropriate for problem solving in complex systems because there is experimentation and learning going on in many places of such management systems. Social networks that combine information and knowledge, decisions and actions across temporal and spatial scales appear essential for successful ecohydrological catchment management. Further research is needed in this area and there is scope for broad-based transdisciplinary collaboration towards successful solutions, especially for those involved with freshwater issues for sustainable catchment management and integrated water resources management.

5. CONCLUSION

Far too often managers seek to command-and-control freshwater flows and landscape dynamics for optimal production of target resources in an attempt to stabilize resource outputs and sustain consumption patterns. This is a dangerous road for humanity founded on a mind set that seems to be illiterate about the complex dynamics of living systems and the fundamental dependence of humanity on those systems (Costanza *et al.* 2000). In the era of the Anthropocene we face different, more variable environments with greater uncertainty about how life-supporting environments will respond to inevitable increases in levels of human use. At the same time we are reducing the capacity of these environments to cope with change through the erosion of ecological and social resilience (Folke *et al.* 2002). The combination of these two trends calls for a shift from the existing paradigm of command-and-control for stabilized 'optimal' production, to one based on managing for social–ecological resilience (Gunderson & Holling 2002; Berkes *et al.* 2003; table 3).

van der Leeuw (2000) characterizes land degradation and the creation of vulnerability as a socio–natural process that has occurred throughout history, a process that highlights the importance of the underlying perception of the human–nature relationship. Human drivers of freshwater use and its multiple relations and functions in dynamic landscapes are deeply embedded in cultural values and underlying perceptions or worldviews (Thompson *et al.* 1990) and economic production systems and lifestyles, mediated by institutional factors (Lambin *et al.* 2001).

Facing complex coevolving social–ecological systems for sustainability requires ability to cope with, adapt to and shape change without losing options for future adaptability (Berkes *et al.* 2003). It is not about controlling or removing change. The paradox is that the mental model of optimal management of systems assumed to be stable and predictable has in many respects reduced the potential for development and altered the capacity of life-support systems to buffer change (Holling & Meffe 1996). The less resilient the system, the lower the capacity of institutions and societies to adapt to and shape change. Resilience needs to be strengthened to secure and provide the possibilities for a prosperous societal development. The essential role of freshwater in these complex dynamics and in enhancing resilience has been given too little attention.

Stewardships of freshwater in dynamic landscapes to secure and enhance social and economic development will no doubt be a central issue in the near future. It requires a shift in thinking and management of freshwater as merely a resource to freshwater as the breath of the Earth. It also requires a shift from trying to control and allocate freshwater flows in an optimal manner for various human uses to recognition of the necessity to actively manage the essential role of freshwater in dynamic landscapes faced with uncertainty and surprise. It will require that those involved with freshwater management foster a worldview and vision of stewardship of freshwater as the bloodstream of the biosphere. This broader view of freshwater provides the foundation for hydrosolidarity.

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